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Is Aerodynamics Breaking an Ionic Barrier ?

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I. Introduction

It is not easy, in modern technology, to evaluate the present state of the art with respect to progress just around the corner. But, even 30 years ago, a well informed aeronauticist seriously asked me: " I know your work and I appreciate it, but do you really think that the compressibility of the air will be of practical importance within our lifetime ? " Realizing that this was not a question for "yes" of "no" answer, I replied: "Compressibility is here right now, when within the high velocity zone of a wing a protuberance creates another excess velocity and a rivet head adds its own excess velocity, etc." Even I did not imagine that, within 30 years, our children and their babies would fly commercially in the compressibility range.

I would not like to make his mistake too, in underestimating progress; neither would I like to give my adapted answer, that the ionic barrier has already been broken. The reason is that we have a more delicate situation in which progress may bypass higher aerodynamic speeds and may concentrate on high speed travel in space. The atmosphere is not any more of unlimited altitude and of negligible curvature. At satellite speed of about Mach number 26, or 26 times the speed of sound, aerodynamic lift is no more needed. Even drag can be avoided by going to higher altitudes and thus there is no need for air breathing engines, since the aircraft is merely coasting.

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There will always be starting and landing, but aerodynamical flying on earth is limited, unless somebody insists to reach any place on earth in less than 40 minutes. It is within this limited range of future flying speeds for which the conventional aerodynamicist feels his responsibility for optimum shape of aircraft at steady state flight. With respect to this, his very own territory, the aerodynamicist may ask: " Does the zigzag way of aerodynamic process, starting with the birth of rational aerodynamics early this century and leading across the sound barrier and further the across the heat barrier, take another turn with another re-evaluation of all experiences when the ionization barrier of the air is broken? Or can we finish our job on earth without it ? "

II. Benefits of Ionization

Considering that air behind a front shock of an aircraft does not become sufficiently ionized below a Mach number of 18, or even with additives of alkaline metals, not earlier than a Mach number of 12, the importance of the last minute change to ~~fluid~~ magnetofluiddynamics can easily be minimized. On the other hand there are at least two great expectations for magnetofluiddynamics: (1) Since magnetofluiddynamics is being developed for handling hot matter, plasmas, with temperatures aimed at millions of degrees, it should be the very tool to protect the aircraft against its own mantle of hot air, which is still a major problem after breaking the heat barrier by ablation. (2) Electric switching is obviously superior and, with the use of servo motors, even more direct than any mechanical device to change the aircraft shape for variable conditions. Therefore, the saftey engineer shpuld be on our side when variable sweep, spoilers, and flaps can be substituted by magnetic reactions between the aircraft and the electrically conductive air around it.

III. Troubles by Ionization

There is an immediate reason which makes the ionization of the air necessary to consider, as an added obligation to the external aerodynamicist who cares about the optimum shape of any aircraft within the demands of the customer, whenever he needs a cut-out in the wing for vision or a machine gun; whenever he needs a plastic bubble on the conopy for orientation; or he wants an antenna shaped as a Christmas tree in front of all the metal. As soon as the mantle of of ionized air surrounds the aircraft at a Mach number above 15 or 18, the aircraft puts itself in a Faraday cage and its radio communication blacks out. In many cases the life of the customer depends on communication at all times. Thus, we are by the vary nature of air at high speeds, at another cross road; either to fear the ionized state of the air and to stay away from it, or to conquer is by breaking the ionic barrier. In the latter case we take part in all the benefits offered by magnetofluiddynamics for the electrically conductive air.

There are mainly three great chapters of ideas to break the ionic barrier:

(1) Reestablishment of communication in order to obtain the benefits of magnetofluiddynamics free of penalties

(2) Help in curing the Headaches left after breaking the sound and heat barrier: heat shielding, supersonic boom, and boundary-layer control

(3) New concepts of lift and drag creation, power generation, thrust, control, etc.

IV. Reestablishment of Communication

To reestablish radio communication while the aircraft has surrounded itself with ionized air is mandatory for many unmanned and manned reentry applications. It is not surprising that the proposals to achieve this goal range from application of brute force to rather ingenious methods. Since the high speed motion is causing the trouble in an originally unionized air, the aerodynamicist may be called upon first to cure it.

A flat bottom behind a sharp leading edge would provide an opening toward the earth for radio communication. It is only not very promissing to maintain any edge - let us say by a combination of different ablating materials similar to the achievement of the edge on non dripping wax candles - since it is already the best ablation material available which forms blunt noses at these high Mach numbers. Another method is to maintain an ablating antenna ahead of the nose by pushing it continuously foreward like the welding rod in a blow torch.

A more sophisticated method is the ejection of halogens or electro-negative compounds. Negative ions, being heavier, have a much reduced mobility compared with free electrons. However, this process, if at all possible, would reestablish the communication by spoiling the chances of magnetofluiddynamics simultanuously. Magnetofluiddynamics prefers the opposite effect accomplished by ejections of alkaline metals or electro-positive compounds. It can, of course, be imagined to use the aircraft body or wing as a separator between ejections of halogens toward the earth for better communication, and ejections of alkaline metals toward the sky for better lifting. Though this dual ejection appears far fetched.

A more ingenious method is the proposed application of magnetic windows. The magnetic field is able to do for the two directions perpendicular to the field lines, what added mass is supposed to accomplish in all three directions, namely reduce the mobility of the free electrons. If all these proposals cannot open windows for the customary wave lengthes of communications a change of the wave length must be added.

V. The Heat Shielding Problem of Reentry

Magnetofluiddynamics has become popular as a tool to harness atomic energy by creating controlled fusion at a temperature of several millions of degrees. If there is any hope for this type of development, it would seem that the heat problem caused by reentering vehicles coming from outerspace and which has the equivalent of only several ten thausends of degrees is childs play in comparison. There are, however, substantial differences in the two flow regimes: While the degree of ionization ~~level~~ is high in the atomic case, the degree of ionization ~~level~~ is extremely low at reentry. It almost seems that nature is not quite fair to the aeronautical problem by causing communication troubles at lower ionization as is required for participation on the benefits. Such complaint usually is an outgrow of a temporary situation rather than the statement of a permanent fact. Comparing this transient region with the transonic speed range of accumulated difficulties, gives plenty of hope that the gap will narrow or even disappear while technology is being improved.

When complete shielding by magnetic deflection of the air ahead of the body appears impossible at the given low degree of ionization ~~level~~ of the air, ablation of the body nose may still be the last resort. Nevertheless the ablation rate could be influenced by application of magnetic drag added to the mechanical drag. (The optimum solution of a greater class of permissible variations cannot be worse than the optimum solution of the restricted class completely inside the other one.) In general the magnetic drag has the same overall tendency as has the drag by viscosity, namely to return the friction heat the the same element of the fluid which experienced the drag losses. This is certainly accomplishing the energy conservation with the minimum of book keeping, and the total enthalpy, or, in less exact terms, the total temperature of all streamlines stays constant in such an arrangement. While there is a second law of thermodynamics predicting equalization of the actual temperatures if there is no compensation, there is no similar law for the ~~dynamic~~ total temperature, moreover there is plenty of compensation wherever drag is created, if such were needed. It is, therefore, necessary to investigate more closely the existing exceptions and to develop methods to enlarge them.

Generally when the designing engineer needs familiarity with the smaller details of a phenomenon which, in its bulk, is not in his favor, the problem arises to adapt delicate informations to the engineering language. Cumbersome relations have to be presented in the most helpfull coordinates. In this connection I am always reminded of the work of R. Mollier who created two engineering diagrams, one for the compressible flow, his enthalpy-entropy-diagram, and the other one for binary mixtures, his enthalpy-composition-diagram. In contrast to other diagrams, his graphical representations suggest automatically the right answers. Therefore these "thinking" diagrams played an important role in clearing the air, the first one in breaking the sound barrier, the second one in breaking the heat barrier by ablation.

There should be more "thinking" diagrams when we want to break the ionic barrier.

VI. Magnetic Forces in Plasmas of Low Ionization Levels.

A) Misalignments by velocity dependent forces.

The primary task, to create large magnetic forces in plasmas of very low degrees of ionization ~~ratios~~ is studied in the last couple of years and has led to many puzzling results. Usually the characteristics of electric and magnetic fields have a familiar ring to the aerodynamicist, but there are a few ~~couple of~~ phenomena who do not enjoy the benefit of such a precedent. One of these phenomena is the pseudo-individuality of magnetic lines. While it appears almost possible to treat a magnetic line as being a substance to grab and to hold, the creation of an electric field can allow it to slip away and to be substituted by another magnetic line. This effect is really the Einstein Relativity of magnetic fields, substituting velocity by electric field components. This is a major science for the art to bottle and duct plasmas. The troubles and their cure by creating classes of magnetic lines essentially different from their neighbors is more at home at plasmas of complete ionization than at plasmas of low degrees of ionization ~~ratios~~.

The electric conductivity, or more specifically its reciprocal value, the electric resistivity, has a very close relation to the viscosity of fluids. It even enters the so-called magnetic Reynolsnumber in exactly the same position that is held by viscosity in the flow Reynoldsnumber. Both of them are responsible for the dissipation of energy. Nevertheless, the two properties seem these days to diverge in the light of the Generalized Ohm's Law. At least with all the generalizations of viscosity applied for many purposes, there never was a reason to generalize viscosity in such a manner that the principle axes of shear stress and shear strain in isotropic liquids and gases are not aligned. The corresponding misalignement between electric field and electric current occurs by the velocity dependent forces of magnetic fields on charged particles. There certainly are velocity dependent forces known in mechanics. The well known Coriolis force in rotating coordinate systems is in such a close relation to the magnetic force on charges, that it is standard procedure, to mention them together. It could, therefore, be that aerodynamicists have to learn new features of electric conductivity only because they have not done their own homework, when it was time for it.

The standard example to explain fluid viscosity for gases is the Couette flow of figure 1. There is no speed limitation in the customary derivation of shear stress by regarding the exchange of particles in neighboring layers under the random motion according to their temperatures. Changing to principle axes, however, large shear stresses τ_{xy} at limited gas pressure p_y from wall to wall can make the lowest principle pressure change from pressure to tension, for which there is no place in gases at all. Collisions can push, not pull. This so-called "cavitation danger" in the Couette flow is a result of the complete alignement of the principle axes for stress and strain, though there is a rotation of all fluid elements with the angular velocity $\omega = V/2h$ (V velocity difference of the parallel motion of the walls, h wall distance). Figure 1 shows, that a misalignement of the principle axes of about 15 degrees would eliminate the negative pressure according to Mohr's tension diagram as indicated.

B. Electron Motion

Coming back to the electrical problem, it is possible to represent the influence of the magnetic field on the electric current in gases by a simple transformation of the case without magnetic field (figure 2). Since the side forces caused by the magnetic field are linearly dependent upon the velocity of the charged particles, the problem of interaction can best be presented in velocity coordinates (Hodógraph). On account that figures preferently demonstrate two-dimensional relations, the velocity plane may be chosen perpendicular to the magnetic field pointing into the plane. In other words, the magnetic field has only a positive z component, while the velocity plane is parallel to the x,y-plane of a x,y,z-space. It is the effect of the presence of the magnetic field B, that velocities achieved under acceleration by an electric field start bending around and finally complete a circle in the velocity coordinates whose center is the actual or apparent drift speed of the magnetic field - E/B. It is understandable that according to the frustrating advance on a circle in stead of a straight line the resulting velocity is vastly reduced. The total deviation from the beginning is restricted to 2U/B. To introduce statistical avemages the conventional simplification of using one typical collision is not recommended. It is more correct for small disturbance velocities - including the case of large magnetic fields!- to use a collision probability in relation to time independent of the velocity disturbance - don't hit us, we hit you - this probability assumption leads to an exponential distribution of the population ~~in~~ over different states according to figure 3. It has the rare advantage, besides being correct for small disturbance velocities, that its population center is identical with its collision center. (The assumption of constant life puts the collision center at full life span, the population center at half life span and requires more attention to put the factor $\frac{1}{2}$ on the proper places.) If, now, the straight acceleration, under the action of the electric field alone, is wrapped around the circle representing the change by the presence of the magnetic field, the population center is not a point on the circumference of the circle but a point inside the circle. The exact position is easily integrable with the help of complex numbers. The result is given in figure 4 for a variety of popolation centers assumed on the straight line. The locus inside the circle is the semicircle over the initial radius, old and new positions are on the same ray from the point (marked by a cross) representing the drift velocity of the magnetic lines - E/B. The transformation from the point C' without magnetic interference to the point C with magnetic interference is, therefore, given by "reciprocal radii" calling the length E/B "unity". If the ordinary Ohm's law gave an electron velocity Δv_o without any magnetic field, the expected velocity with a magnetic field present is then given by Δv as indicated in figure 5. But it is even possible to call the vector directly with the name of a current density. It is only necessary to multiply the average velocity difference with the unit of electric charge $\mp$ e and with the number density of negative or positive charges in the volumelement of space n, both number densities are equal in plasmas by their definition as a basically neutre mixture. By the well known convention is the electric current opposite to the movement of the electrons. The ordinary viscosity σ_o in absence of a magnetic field can be used, to plot even electric fields E as velocity vectors in the same coordinates, as equal to the current density j or its velocity value when divided by the charge density e n. The two scaling factors (e n) and σ_o are the only informations required to assemble all information in the same coordinates. This graphical representation is, of course, equivalent ~~the~~ to the equations (1) or abbreviated (2) of the analytic treatment.

Figure 4 indicates a visible reduction in the actual current density as compared to the expected one without any magnetic interference. Since large forces are the aim of creation of lift treated by the authors theoretically and experimentally. Inside the circular cross section of the magnetic field B by the flow of ionized gas an induced electric field perpendicular to the velocity V is created which tries to promote currents j in an oblique direction. The Kirchhoff condition that currents do not exist but closed, makes the full problem a little more difficult than the one short circuited around the magnetic field. The two-dimensional problem of currents outside a circle has the simplified result, that the external region is equivalent the internal region. Thus the closing outside without magnetic interference affords again the Ohm portion of the electric field inside. The total induced electric field is, therefore, achieved by accepting once the Hall component E_{HALL} but doubling the Ohm component E_{Ω} parallel to j. The volume forces $f = j \times B$ are only created inside the magnetic field and have a smaller angle between their direction and the direction of the final flow velocity V. By applying stronger magnetic fields, any acute angle between f and V can, however, be achieved. The drag component has to pay for both the internal and the external creation of ohmic heat; both parts consist according to the quoted equivalence of an equal amount.

D. Lift by Hall Effect and Shape

No engineer, worth his salt, would ever leave this problem in this state. It hurts to pay for unnecessary heat, even more/for lift, which has no minimum cost whatsoever. He likes to show his talent by giving the magnetic portion of the arrangement a more adaquate shape. There is no doubt that curiosity is more aroused by the circular shape of figure 5, but engineering starts with variation of the shape. Figure 6 represents the case of an elliptical cross section of the magnetic field with an axis ratio $a/b = 2:1$. The necessary external field for closing the currents is known by conformal mapping. The outside losses are only half the inside losses if the current is parallel to the large axis, but they are twice the internal losses if the current is turned parallel to the small axis of the ellipse. The locus of all necessary external field requirements, if the ellipse is turned around, leads to a circle with the known points, half and double the internal value, terminating the diameter. Proportionality between the induced electric field and the flow velocity at a given magnetic field and the orthogonality of the two vectors are the reasons, that the locus for all necessary flight velocities for a given internal current density is again a circle, indicating the starting point for the vector V. The practical problem, being to find forces for given velocities, is, of course, the reciprocal relation to the plotted case of unknown velocities for given forces. This ~~differ-~~ reversal [illegible] influences to a certain degree the proper choice of the true points for a) high lift, b) high drag, c) low [illegible] reciprocal relations on circles for a pencil of rays is elementary geometry. It is, therefore, not hard to find the four points a'b'c'd' on both of the circles.

E. Drag by Hall Effect and Shape.

The example of high drag for reentry applications is represented in figure 7 on another ellipse with the axes ratio $a/b = 4:1$. Added to the actual example are the high drag points on both the induced electric field circle and the flight velocity circle for all axes ratios 1, 2, 4, and ∞. While at the assumed magnetic field intensity and the resulting tilt between internal electric field and current even the axis ratio 4:1 never underbids the internal field strength E_{INT}. Thus, it almost underlines the experience ~~with~~ on untilted field to current relations, that the external closing is an additional burden. The case of infinite axis ratio demonstrates that here are different conditions. ~~The case of infinite axis ratio reduces~~ The necessary induced field ~~to~~ only the component parallel to the current vector j. The Hall component is saved. Similar, not quite so ~~favourable~~ complete savings can be made by high finite axis ratios or larger original angles between electric field and current. The result is that a certain outside field is quite welcome. Even the actually depicted case with the ellipse 4:1 pays very little for the external closing of the currents.

F. Nose Cone Electrically Isolated Versus Conductive.

The practical implications of the lessons, learned by investigating elliptical shapes for the magnetic region, are demonstrated by comparing a nose cone in figure 8 with a conductive skin and a nose cone in figure 9 with isolated skin. The returning currents in figure 8 through the skin are not charged with Ohm's losses inside the skin of a sufficient depth. In figure 8 the primary induction field E_{IND} perpendicular to the oncomming flow velocity V has no difficulty to close its favorite current, since both the return through the skin and the closing after one turn around the body is free of any external burden. Thus the internal electric field consumes just the induced field and its favorite current becomes reality. The volume forces $f = j \times B$ are oblique, giving a ~~small~~ reduced component for drag, using the other component for a torque. Both components have to be payed by ohmic heat ~~and by~~ out of the product drag times velocity.

In figure 9 the return path of the current is blocked. The original current, with its longitudinal component, creates a space charge because of this blockage, till the resulting electric field is satisfied with a current in circumferential direction only. The electric field of the space charge E_{SP} ~~added to~~ and the originally induced field E_{IND} add to a total field, to which the circumferential current is now the favorite current. No external currents are required. It is perfectly healthy, to ask about the apparent velocity of the plasma with respect to the magnetic lines, which would create the total field E_{IND} plus E_{SP}. The answer is the velocity V with a certain circumferential component added. Since the flow cannot twist around in this manner, the magnetic lines could do the circumferential part by spinning like a lefthanded propeller. Comparing the two extremes of high conductivity and zero conductivity of the nose skin, as pictured in the figures 8 and 9, and adding some finite conductivities to change from one to the other, it is unavoidable to see, that the magnetic lines have a tendency to spin. The torque on the lines is either taken over completely by the back straps of the electric currents ~~by~~ with their force $I \times B$ in the magnetic field, or they themselves begin to spin ~~somewhat~~ under load. Only the extreme case of no back straps brings the magnetic lines to the idling propeller condition of no load in figure 9. The south pole S inside the nose does not care about the twisting of its tuft of magnetic lines. The spinning of the magnetic lines is proper application of the magnetic relativity. The reality of this movement is not discussed by relativity and we are fortunate that the ionized layer is of finite thickness to stop further talk.

G. Ion Slip.

Up to now, the electrons were considered the only group of particles not going with the other crowd. Stronger magnetic fields can also separate the positive ions from the neutral particles between collisions. Qualitatively everything is similar to the former case of electron movement. The charge is, of course, reversed, and the mass is about 55 000 times heavier (take NO^+ as the most probable constituent for positive ions in air). The result for ions in a gas of low degree of ionization puts the upper semicircle in figure 10 in operation for the positive current j_+ while the current of electrons j_- in the lower semicircle is probably close to the end of its journey. The conductivity has to be broken up in the parts σ_+ and σ_-, with a ratio not quite as high as 1 : 55 000, but rather near the square root of this value 1 : 240 as an order of magnitude reminder. The anlytical treatment of equation (1) and symbolic equation in (2) can be generalized symbolically in equation (5) and spelled out in equation (6).

In the process of giving the enigineer not only the puzzling features of the magnetic interference but reliable representations, I have to ask for poetic licence with respect to the superposition of the negative and the positive charge movements. The first separation from the crowd creates a binary mixture, the second separation a ternery mixture, no matter who separates first. While in a binary mixture one friction coefficient governs all relative motions, in the ternary mixture are not two, but three friction coefficients needed. Only the case of one bulk crowd with traces of two other ingredients gets away with two important friction coefficients.

Even in this case of very low mixture ratios there is a danger to confuse the mass ratio of the two ingredients 1 : 55 000 with the friction ratio 1 : 240, the common population center and the common collision center etc. My apology for neglecting the philosophy of ternary mixtures for the sake of simplicity in this paper may ~~n~~ be born out of my own work in mixtures. The simplified and widely used representation restores, of course, parity in case of positive and negative ions of equal mass and equal cross section automatically.

When the electron movement by itself did not cost more ohmic heat for the actual current, the adding of ion movement or ion slip is costly. The parallel component of the electric field with respect to the current is too large. The extra heat in the second term of equation (7) is positive and equals the force $f = j \times B$ multiplied with the velocity distance of the "friction center" of the total current j from the origin - the friction center cuts the vector in the ratio σ_+ / σ_- - these two vectors are parallel and indicate the friction loss to carry along the bulk of neutrals. The maximum value of the conductivity, which is available if the Hall component is treated in the best possible way, is reduced with respect to σ_0 by a term containing the square of the magnetic field normal to the current, B_n^2.

H. The D.C. Accelerator.

To demonstrate the value of a representation containing not only the resulting current j but also its parts j_- and j_+, the example of the $j \times B$ or the D.C accelerator is given in figure 13. All relations are in an oblique fashion and the designing engineer has to find his way through them, having only the exact value of the magnetic field ~~str~~ strength as an additional variable not visible in figure 13. Rotating figure 12 to a favorable position can do just one of several choices. If the application of two long electrodes is the choice, the resulting force and the currents are tilted. If the ~~electrons are~~ current is closed through the wires on the outside applying multiple sets of electrodes, the side movement of the positive ions can be avoided as in the presented case of no "electrolysis". The acceleration force is still tilted, but the bulk of the neutrals can develop a small pressure differential between both walls to compensate for that. The conservation of the positive ions ~~or~~ over a long accelerator length could indeed be the most important point of view, if the~~y~~ ions are made by a slowly adjusting equilibrium or by seeding with foreign additives. The purpose of the diagram is to leave the decision to the completely informed designer.

VII . Conclusion

In conclusion I like to come back to the basic question of aerodynamic applications, what are the chances of magnetofluiddynamics to provide adequate forces between the aircraft and the surrounding mantle of ionized air. While in reentry drag and heat have to be weighted against each other, there still is a request of a minimum force. Since flight speed V is given, the other factors are conductivity σ_0 and the square of the magnetic field B^2. These four factors determine the drag per unit volume, while the aerodynamic forces are per unit of area and the dynamic pressure V^2 times the air density ρ or one half of it, to be conventional. While in the aerodynamical case every single factor counts, the magnetofluiddynamical case is quite exceptional. An infinite conductivity would not solve the problem, neither an infinite magnetic field.

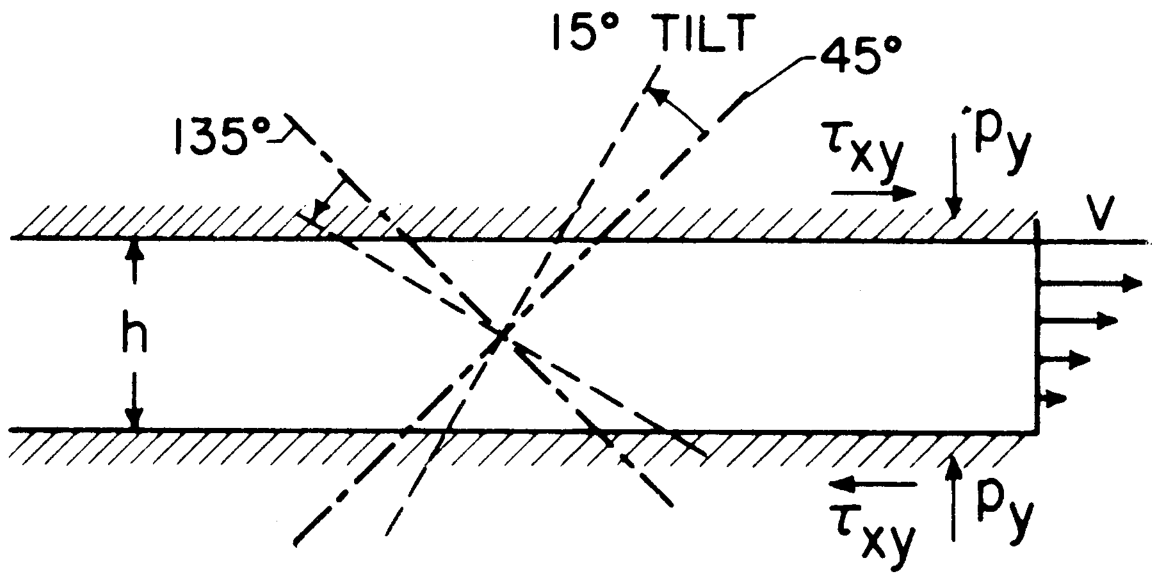
If the conductivity is large, the induced currents add their own magnetic field to the given magnetic field and do it, according to Lenz's rule of induction, by diminishing the effect. Hall, as is demonstrated in the chapter VI.G, including the ion slip, does not give the magnetic field an unlimited influence. The usefull, generalized conductivity σ_{max} of equation (9) finally diminishes inverse to B^2 and stops the growth of the force by the other factor B^2. Both Lenz and Hall have to be observed and show that the most successful increase is on the smaller of two terms in the denominator of equation (18) or (19). If the conductivity is superior, the Lenz limit of the magnetic field strength becomes dominant. If the magnetic field is superior, the Hall limit makes itself felt. On this limit the charged particles are almost stopped by the magnetic field. ~~and~~ The drag forces correspond to the "filter friction" on the neutrals by the filter of arrested charged particles.

Practically we are only at one tenth of the conductivity and one tenth of the magnetic field strength where these effects come into play. There is still ample of ~~improvement~~ slack for future improvement. If both variables gain a factor ten, the magnetic forces are a hundered times larger than the aerodynamical forces in similar dimensions. The main point, that I like to convey, is the fact that the possibilities depend to great extend on skill, to find new twists and tricks in these misaligned relations. The ~~greatest enemy~~ worst enemy of rigid mathematical proofs is the designing engineer, who accomplishes the "impossible" by simply violating the assumptions of the proof. For him I have high hopes in breaking the ionic barrier.

TILT OF PRINCIPLE AXES

COUETTE FLOW

$\omega = \frac{V}{2h}$



σ - τ - DIAGRAM OF MOHR

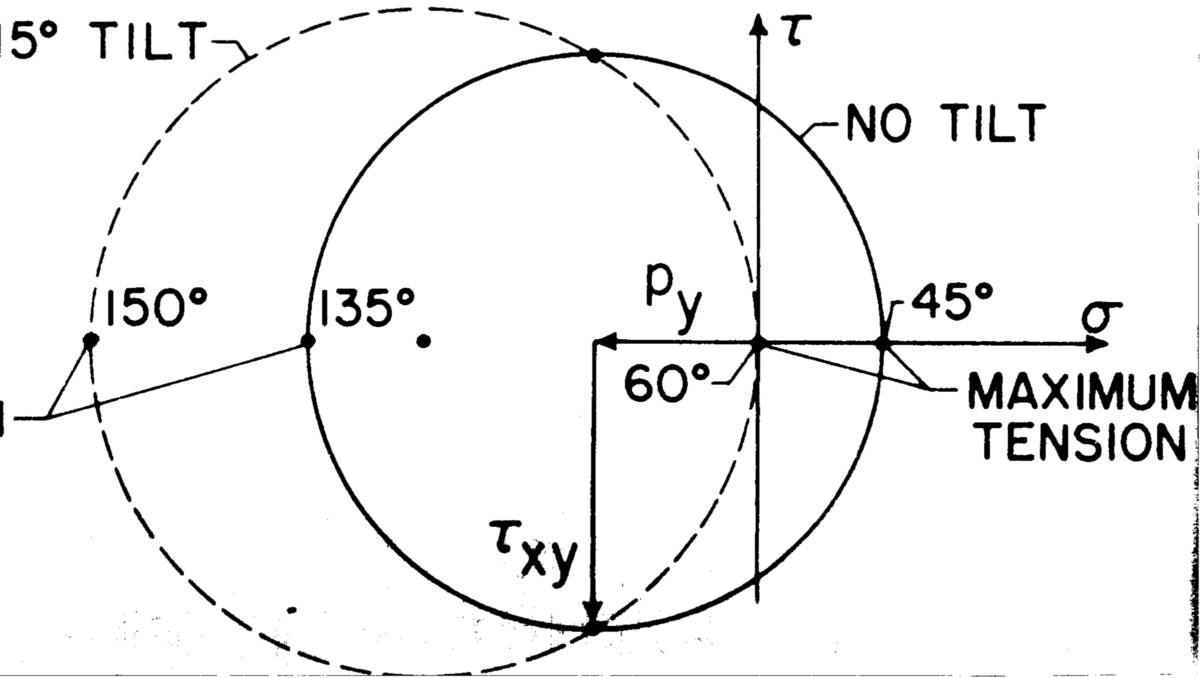
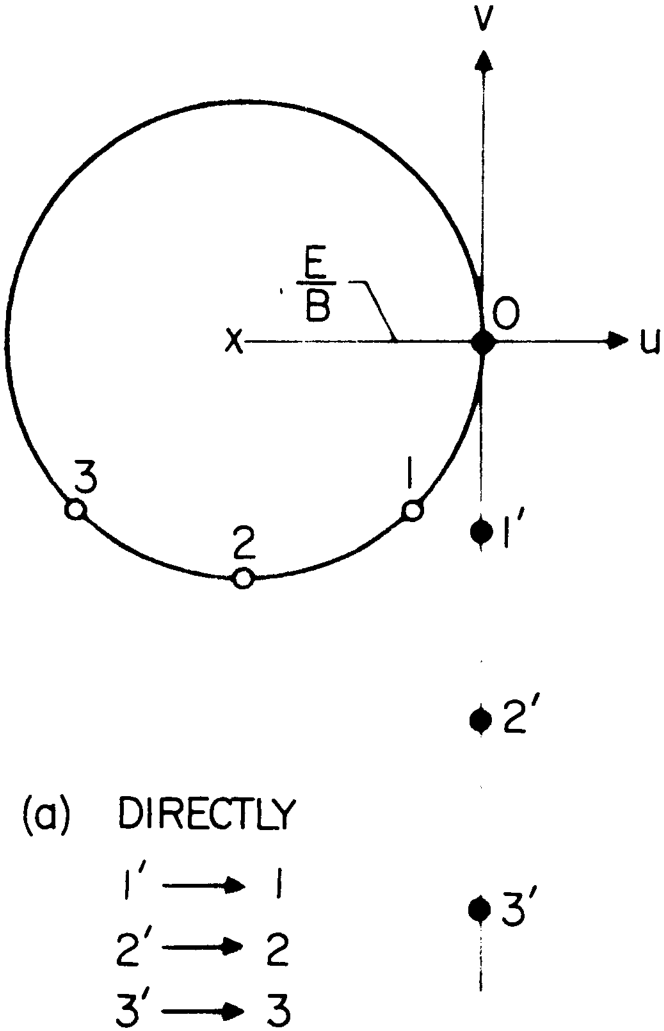
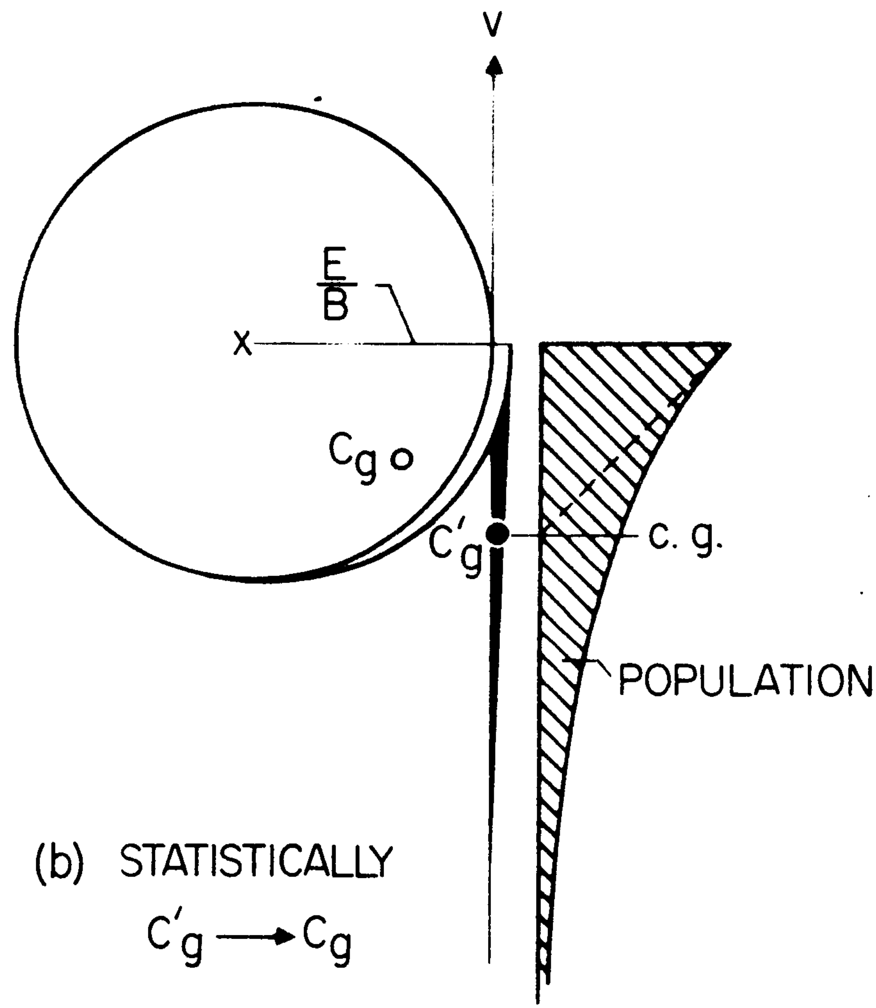


Fig. 1.

VELOCITY-PLANES





CIRCULAR VERSUS STRAIGHT ACCELERATION

Fig. 2

Fig. 3

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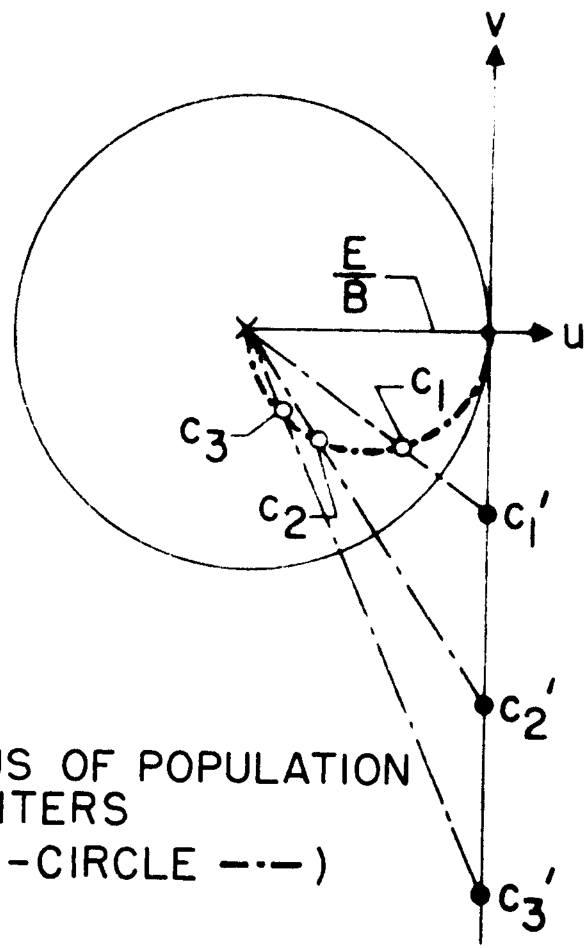
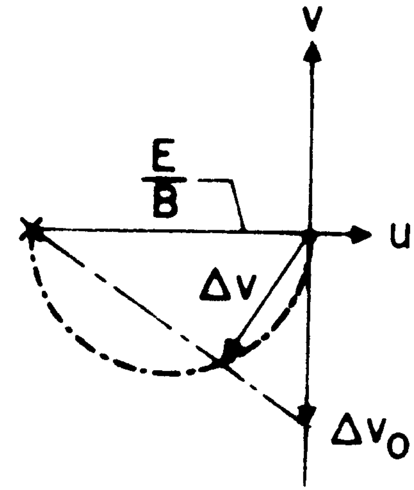
VELOCITY PLANES



(a) LOCUS OF POPULATION CENTERS (SEMI-CIRCLE –·–)



(b) RESULTING VELOCITY $\Delta v_0 \rightarrow \Delta v$

ACCELERATION IN PRESENCE OF MAGNETIC FIELD

Fig. 4

Fig 5

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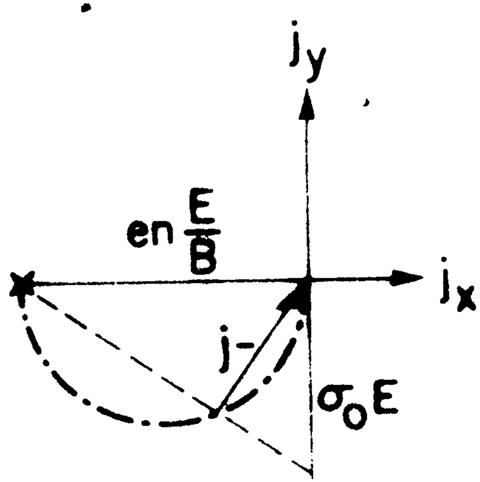
HALL EFFECT

ELECTRIC CURRENT PLANE



$j = \pm e n \Delta v$

Fig. 6

$\mp e$ = CHARGE OF ELECTRON, ION

n = ELECTRON DENSITY

E = ELECTRIC FIELD

B = MAGNETIC INDUCTION

j = ELECTRIC CURRENT DENSITY

σ_0 = ELECTRIC CONDUCTIVITY (AT ZERO MAGNETIC FIELD)

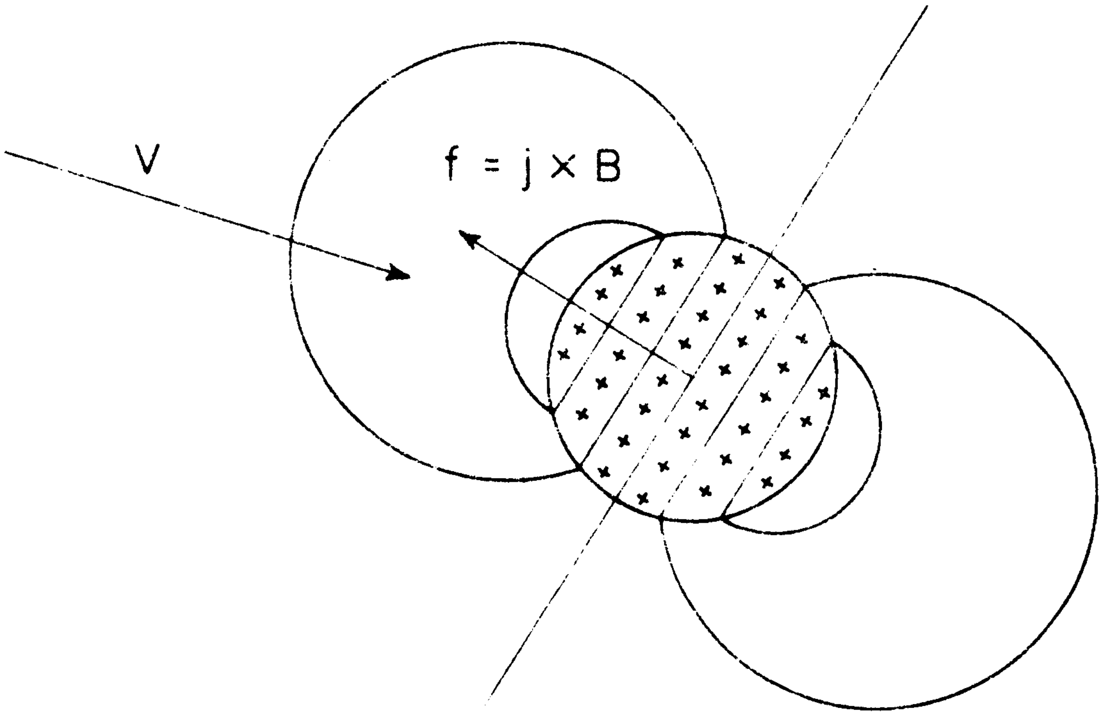
(2) $$j\left(1 + \times B \frac{\sigma_0}{en}\right) = \sigma_0 E$$

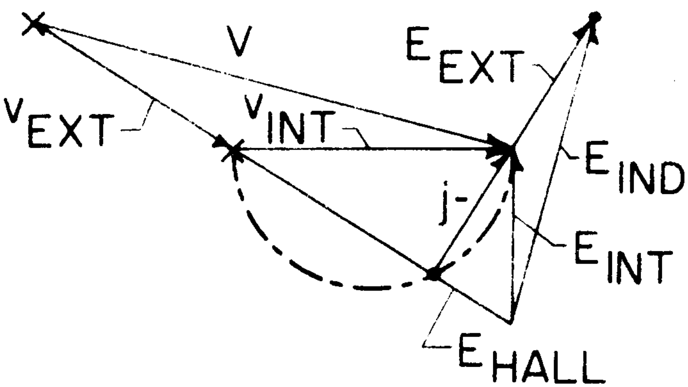
(1) $$j + j \times B \frac{\sigma_0}{en} = \sigma_0 E$$

(3) OHMIC HEAT: $$Q_\Omega = E \bullet j = \frac{j\left(1 + \times B \frac{\sigma_0}{en}\right) \bullet j}{\sigma_0} = \sigma_0 j^2$$

(4) OR IN E: $$Q_\Omega = E \bullet j = \sigma_0 \frac{1 + \left(\frac{\sigma_0}{en}\right)^2 B_E^2}{1 + \left(\frac{\sigma_0}{en}\right)^2 B^2} E^2 = \sigma_1 E^2$$

LIFT BY HALL - EFFECT

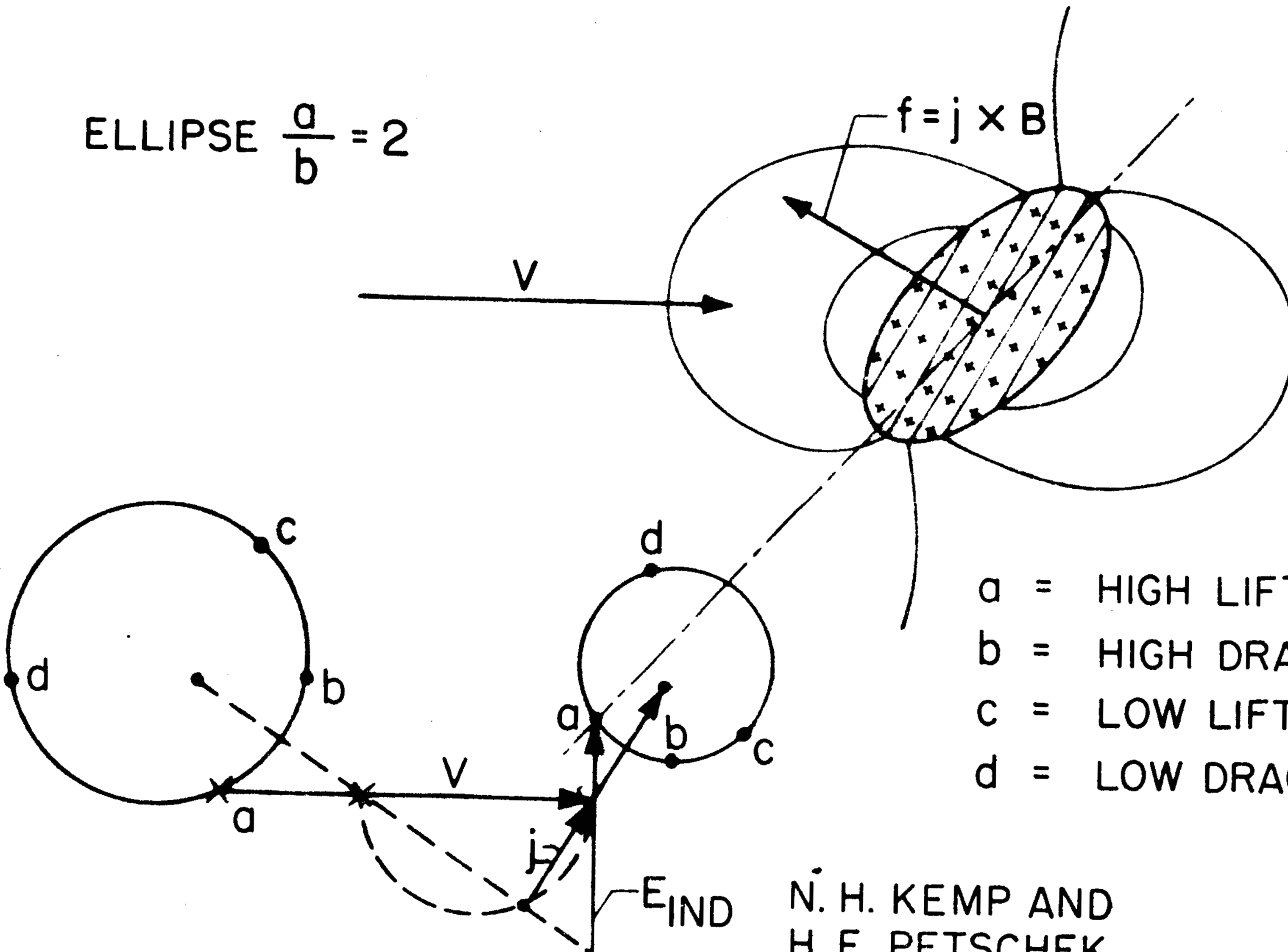




N. H. KEMP AND
H. E. PETSCHEK

Fig. 7.

MORE LIFT BY SHAPE AND HALL EFFECT



a = HIGH LIFT
b = HIGH DRAG
c = LOW LIFT
d = LOW DRAG

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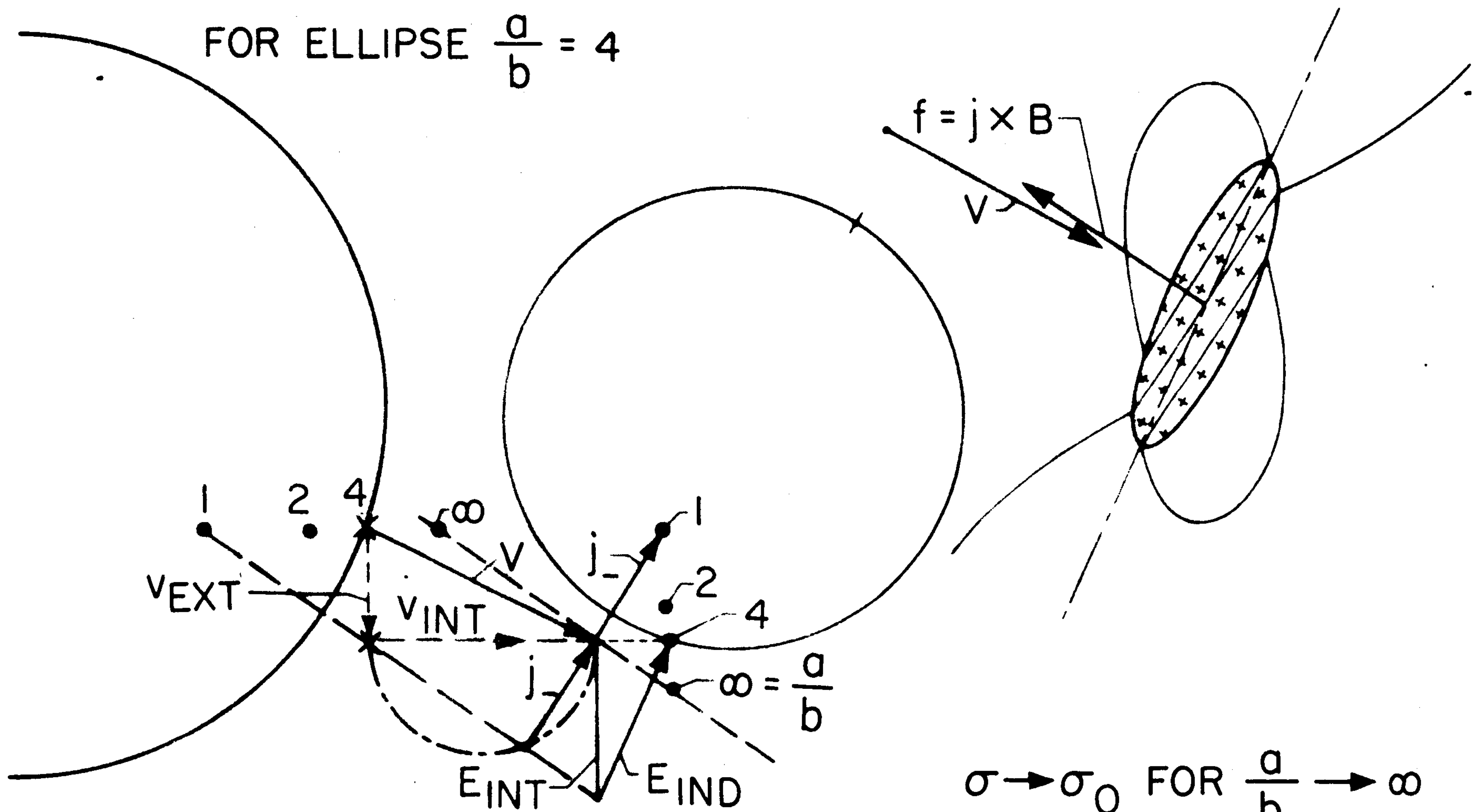
HIGH DRAG BY SHAPE AND HALL EFFECT



$\sigma \rightarrow \sigma_0$ FOR $\frac{a}{b} \rightarrow \infty$

Fig. 9

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MAGNETIC DRAG

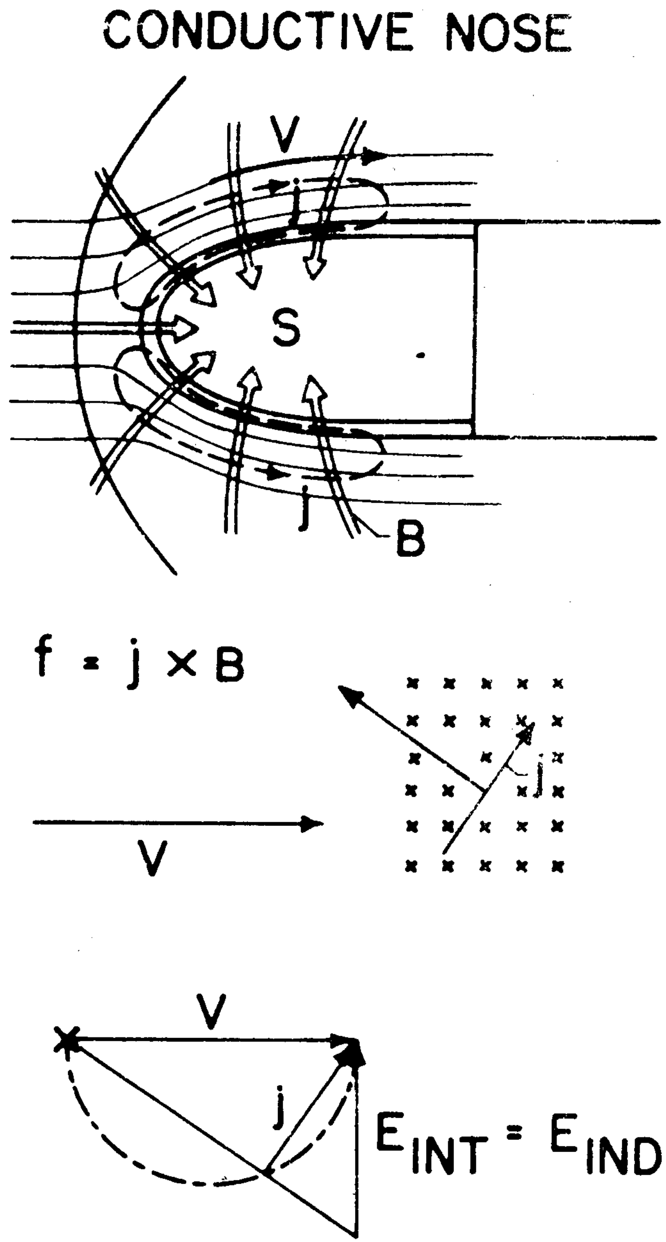

Fig. 10

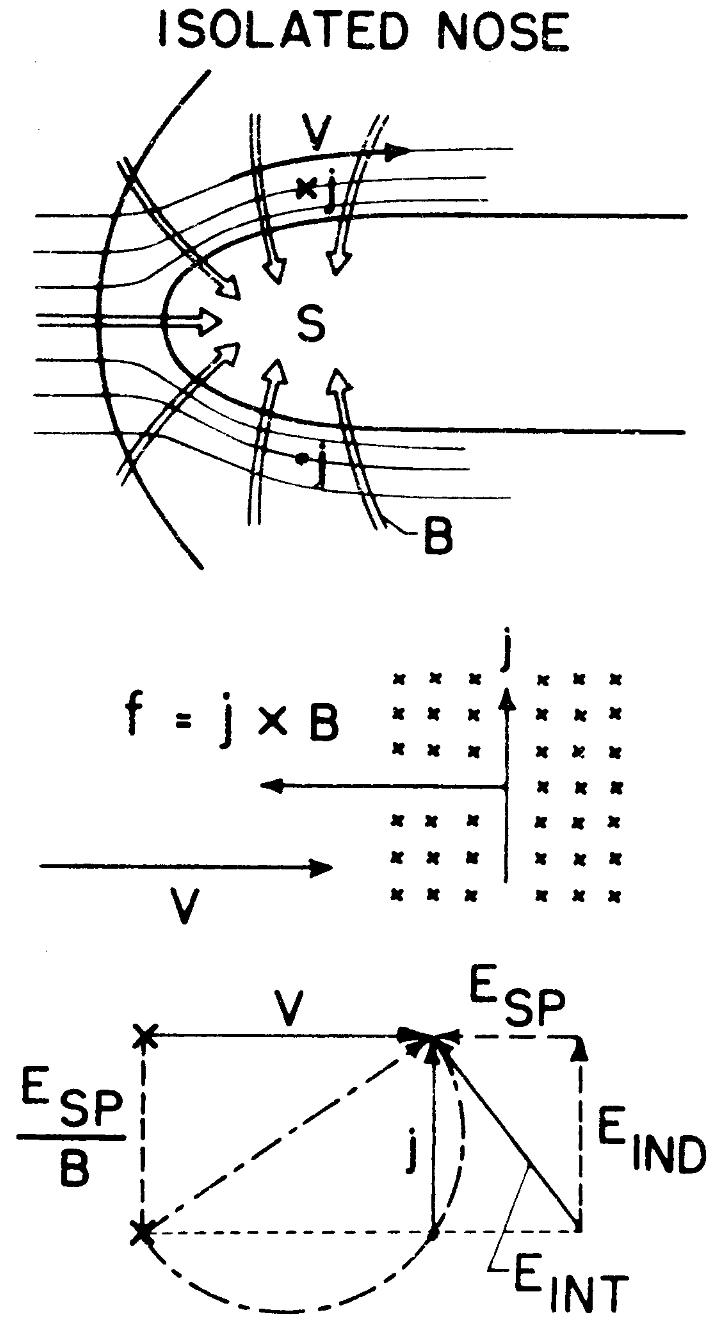

Fig. 11

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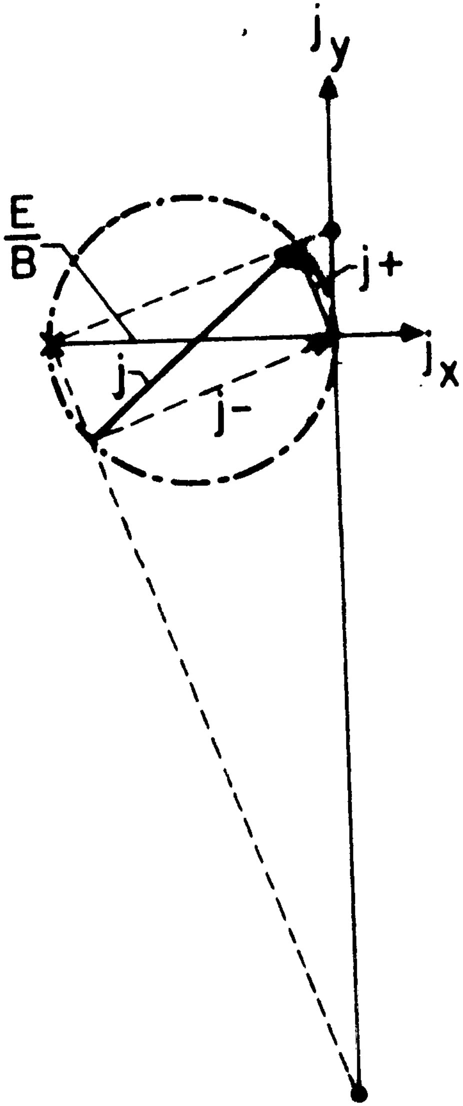
EFFECT OF ION MOVEMENT (ION SLIP)



ELECTRONS: $$j\left(1+\times B\,\frac{\sigma_0}{en}\right)=\sigma_0\,E \qquad (4)$$

ELECTRONS + IONS $\left(\sigma_-/\sigma_+ \approx 240\right)$:

$$j\left(1+\times B\,\frac{\sigma_-}{en}\right)\left(1-\times B\,\frac{\sigma_+}{en}\right)=(\sigma_+ + \sigma_-)E \qquad (5)$$

WHICH MEANS:

$$j + j\times B\,\frac{\sigma_- - \sigma_+}{en} - (j\times B)\times B\,\frac{\sigma_-\sigma_+}{e^2 n^2}=(\sigma_+ + \sigma_-)E \qquad (6)$$

$$Q_\Omega = E\cdot j = \frac{j^2 - \frac{\sigma_-\sigma_+}{e^2 n^2}\left((j\times B)\times B\right)\cdot j}{\sigma_+ + \sigma_-} \qquad (7)$$

$$= \frac{1+\frac{\sigma_-\sigma_+}{e^2 n^2}\,B_n^{\,2}}{\sigma_+ + \sigma_-}\,j^2 \qquad (8)$$

$$\sigma_0 \equiv \sigma_+ + \sigma_- \rightarrow \frac{\sigma_0}{1+\frac{\sigma_-\sigma_+}{e^2 n^2}\,B_n^{\,2}} = \sigma_{MAX} \qquad (9)$$

Fig. 12

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LIMITING FORCE RATIOS

BOTH CORRECTIONS APPLIED

(18) $$\frac{F_m}{F_a} = \frac{\mu_0 \sigma_0 VL}{1 + \frac{\sigma_+ \sigma_-}{e^2 n^2} B^2 + \mu_0 \sigma_0 VL} \qquad \frac{\frac{1}{2\mu_0} B^2}{\frac{1}{2} \rho V^2} \longrightarrow \frac{P_m}{P_a}$$

OR

(19) $$\frac{F_m}{F_R} = \frac{\frac{\sigma_+ \sigma_-}{e^2 n^2} B^2}{1 + \mu_0 \sigma_0 VL + \frac{\sigma_+ \sigma_-}{e^2 n^2} B^2} \qquad \frac{\frac{e^2 n^2 \sigma_0}{2 \sigma_+ \sigma_-} VL}{\frac{1}{2} \rho V^2} \longrightarrow \frac{L}{\lambda_+} \frac{n m_+}{\rho}$$

(20) $$\sigma_- = \frac{e^2 n}{m_-} \frac{\lambda_-}{c_-}$$ (21) $$\sigma_+ = \frac{e^2 n}{m_+} \frac{\lambda_+}{c_+}$$

(22) $$\frac{\sigma_- B}{en} = \frac{eB}{m_-} \frac{\lambda_-}{c_-} = \omega_- \tau_-$$ (23) $$\frac{\sigma_+ B}{en} = \frac{eB}{m_+} \frac{\lambda_+}{c_+} = \omega_+ \tau_+$$